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REVIEWS

Geodetic Operations in the United States 1903–1906. A Report to the Fifteenth General Conference of the International Geodetic Association. By O. H. TITTMANN and J. H. HAYFORD. Washington, 1906. Pp. 45.

While this paper embraces, as indicated, a statement of the principal operations of the Coast and Geodetic Survey for 1903–6, its chief contribution relates to the figure of the earth. The part of special interest to geologists is that which deals with the relation of variations of density in the outer part of the lithosphere to the great surface reliefs. The investigation bearing upon this point was based wholly on the deflections of the vertical, no use being made of determinations of force of gravity. The area treated extends over 18° 51′ in latitude and 50° 7′ in longitude. Astronomic determinations of the deflection of the vertical to the number of 507, all connected by continuous primary triangulation, were used.

It has long been known that the force of gravity on the surface of the earth is not distributed as though the sub-surface material were either homogeneous, gravitatively, or symmetrical. The investigation set forth in this paper, while fully confirming this, goes much beyond any previous inquiry in determining the nature of the inequalities in the distribution of gravity and their correlation with topography. It thus constitutes a very notable advance in this important line of research. The deflections of the vertical that are assignable to variations in the topography, considered by itself alone, were first determined in a very comprehensive way, the effect of the reliefs within a radius of 4126.4 kilometers being computed for each station. The results clearly indicated that the material of the protuberances, viewed largely, has less inherent gravity than that of the basins—a conclusion in accord with the general tenor of previous inquiries in different periods of the world. It remained therefore to determine the distribution of the internal inequalities of density thus disclosed.

The essential feature of the problem was to find out whether the differences of density are so distributed that the continental and oceanic columns balance one another or not, and, if they do, at what depth the equation is established. A series of hypotheses relative to this were adopted as the bases of trial solutions. While these hypotheses, so far as they enter into the real inquiry, related solely to the distribution of gravity, they have been associated by the authors with ideas of rigidity and isostasy, the purpose of this undoubtedly being to give to the inquiry a definite relation to geophysical problems. While this purpose is eminently laudable, it is not clear to the reviewer that this particular association with questions of rigidity and isostasy is altogether happy, as will be indicated later. These terms will therefore be omitted from the following statement of the hypotheses on which the trial solutions were based, though the term "isostatic compensation" will be retained as a convenient expression of gravitative equilibrium reached by variation in density.

Five trial solutions by the method of the least squares were made on the basis of five hypotheses of the distribution of density, as follows:

Solution A was based on the assumption that there is a complete isostatic compensation at the depth zero beneath the ocean floor; that there exists immediately below every elevation a defect of density fully compensating for the elevation, and that at the very surface of the ocean floor there lies material of the excessive density necessary to compensate for the depression of this floor.

Solution B was made on the assumption that the portions of the continent above the sea-level are excesses of mass, and that the oceans represent deficiencies of mass, and that no isostatic compensation exists; or, in other words, the solution was based upon the supposition that, if isostatic compensation exists, it is uniformly distributed through an indefinite depth.

Solution E was made on the assumption that isostatic compensation is complete and uniformly distributed throughout a depth of 162.2 kilometers.

Solutions H and G were of the same type as E, but based on the assumptions that the depths of compensation are 120.9 and 113.7 kilometers respectively.

The sums of the squares of the residuals of these different solutions were as follows:

Solution A, depth of compensation zero	13,837
Solution B, depth of compensation infinity	65,104
Solution E, depth of compensation 162.2 kilometers . . .	8,174
Solution H, depth of compensation 120.9 kilometers . . .	7,987
Solution G, depth of compensation 113.7 kilometers . . .	7,983

It is to be noted that in Solutions E, H, and G the density compensation is assumed to be *uniformly* distributed to the depths named measured from the varying surface of the lithosphere. Of these solutions, G, having the smallest sum of the squares of the residuals, is regarded as the closest approximation to the truth.

It thus appears that the inferior densities and greater protuberances of the continental reliefs are such that their joint gravitative effects are balanced by the greater densities and negative protuberances of the oceanic basins at a depth of about 114 kilometers, or 71 miles, if the deficiencies and excesses of density respectively remain uniform to this depth. It was not found possible, however, to determine, from the observations on the deflection of the vertical now available in the United States, whether this or some other was the actual mode of distribution of the compensating densities. The authors recognize, as a possible alternative, a distribution in which the compensating differences of density are greatest at the surface and decline uniformly to a vanishing point, which would be reached at a depth of about 109 miles. The authors speak of the former mode of distribution as more probable than the latter, but whether this is based upon considerations growing out of the reduction of the observations or upon geophysical views is not indicated. From the geological point of view, it seems to the reviewer that a decline in differences of density from the surface to a vanishing point is much more probable than uniform differences ceasing suddenly at a given horizon. It seems, furthermore, that a varying decline from a maximum near the surface to a vanishing point in depth is more probable than either. Especially does it appear probable that a vanishing differentiation below represents the true condition when account is taken of the great depth to which the compensating densities reach as disclosed by this investigation.

A vanishing differentiation of density, rather than a uniform one ceasing abruptly, would seem to be probable under any recognized hypothesis of the origin and mode of formation of the earth that is built upon consistent and plausible grounds. None of the older current hypotheses respecting the mode of formation of the earth, so far as we know, postulates a lateral differentiation of densities at so great a depth as 70 to 100 miles; but if these hypotheses are modified so as to be brought into conformity with these new determinations in the matter of depth, it would seem that, to be consistent with the conditions of the case, they must, in all probability, involve increasing horizontal differentiations from the lowest horizon at which these were developed to the surface, and that these would most probably have a differentially varying value.

The theory of accretion from planetesimals is perhaps the only one which has definitely postulated a horizontal differentiation of densities at horizons of so great depth. It specifically assigns to the continental and oceanic sectors differences of specific gravity reaching to these and greater depths, and attributes them to differential weathering supposed to have begun at a relatively early stage in the growth of the earth, and to have increased upward at more than a simple ratio until the surface was reached.[1] The effects of the original differentiation by weathering are supposed to have been subsequently modified by vulcanism in such a way that the lighter portions of the differentiated material were brought to or toward the surface in larger percentage than the heavier material, the effect of which was to concentrate the differences of density previously developed toward the surface. The final differentiations of density thus postulated would therefore be greatest at the surface, and would decline downward at a varying rate, whose nature may be roughly indicated by the curve *C–C* in Fig. 1, where it may be compared with the rectangle *AAA* and with the triangle *ABB* which represent the two modes of compensatory distribution referred to above. So far as the reviewer can judge from an inspection of the data furnished by the paper, a distribution of densities such as is represented by the curve *C–C* would satisfy the requirements of the observations as well as either of the others. It would seem, therefore, to be a matter of some felicity that the accretion hypothesis should have assigned, on its own grounds and as the inevitable result of the processes it postulates, a specific differentiation and distribution of densities in fairly close accord with these new determinations based on wholly independent considerations.

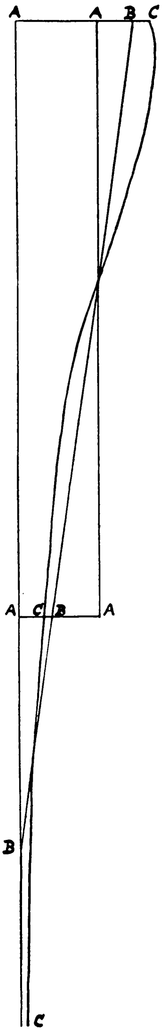

FIG. 1

The authors speak of Solution B as being based on the supposition that the earth is rigid, and of Solutions E, G, and H as though they represent isostasy. They say that the investigation "*leads to a definite and positive conclusion as to rigidity versus isostasy.*"[2] They add:

> For the United States and adjacent areas, the assumption of extreme rigidity is far from the truth. On the contrary, the assumption that the earth is in the condition called isostasy is a comparatively close approxima-

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[1] Chamberlin and Salisbury, *Geology*, Vol. II, pp. 107–11.

[2] P. 10; italics theirs.

tion to the truth. In other words the United States is not maintained in its position above sea-level by the rigidity of the earth, but is, in the main, buoyed up, floated, because it is composed of material of deficient density.[1]

So far as the reviewer can see, that which is really determined does not extend beyond the distribution of density, and all that is added to this is inference or interpretation. It is therefore consistent with the very highest appreciation of the value of the determinations to question the validity of these superimposed interpretations.

The authors are probably entirely correct in assuming that the distribution of specific gravities postulated in Solution B could not be maintained without great rigidity in the deeper portion of the earth. It is equally beyond the probabilities that such a distribution of matter could ever have arisen under any tenable hypothesis of the mode of the earth's formation. But, while the maintenance of this unrealizable condition of things is excluded by the investigation, it is not apparent that it excludes rigidity under more tenable conceptions of the formation of the earth. The exclusion of an extreme and indefensible hypothesis does not logically cover all other hypotheses. It is possible that the authors did not really intend to convey the impression that the conceptions of rigidity held by certain physicists and geologists were incompatible with their determinations, but their language seems to imply this.

So, on the other hand, when the authors say "The United States is not maintained in its position above sea-level by the rigidity of the earth, but is, in the main, buoyed up, floated, because it is composed of material of deficient density," their language carries the impression of a positive affirmation of liquidity or viscousness at the base of the crust in which the differentiated densities reside. Such is the usual conception that goes with the term "isostasy" as it has been used in geological literature. Now, that which is really demonstrated in this important investigation is simply that the compensation of densities becomes approximately complete somewhere between 50 and 150 miles below the surface. The agencies which have produced this differentiation of densities and the physical conditions which now maintain it do not seem to be really touched by the investigation, but to be matters of inference or interpretation based upon other considerations. In the judgment of the reviewer, this differentiation may have arisen and may be now maintained without involving any nearer approach to fluidity than that which is manifested by bodies whose rigidities range from the best granite to the best steel and beyond. Deformations by molecular transfers from crystal to crystal without essentially affecting the state of rigidity ought now to be regarded as at least a plausible, if not an established, geophysical process, as urged by Van Hise and others in relation to the so-called flowage of crystalline rock, and by Chamberlin and others in relation to the so-called flowage of glaciers. A condition of gravitative balance essentially equivalent to that arising from isostatic flotation may thus be reached in great masses of matter which are at every instant and in all parts affected by a high degree of rigidity. Under this conception the protuberant area of the United States may be supported by a base which is rigid in the truest sense of the term. In this case it could be said to float on its base in no more appropriate sense than the Greenland ice-fields may be said to float on their rock bottom.

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[1] P. 10.

There is a specific objection to entertaining the conception of a crust of 70 or 100 miles floating on a mobile substratum. A crust of that thickness, if formed of the firmest granite, would still have but a limited power of accumulating lateral stresses, and hence must yield to such stresses as fast as they reach a moderate magnitude and give rise to practically continuous folding. It is, however, quite certain that most mountain foldings took place in relatively short periods. We seem therefore to be shut up to the alternative of supposing either that the agencies which produced mountain foldings came into play for short periods only and then ceased, or that the body of the earth is capable of accumulating stresses for a long period until, having attained large magnitude, they reach the limits of resistance and deformation ensues in a comparatively short period. The former hypothesis does not seem to the reviewer to have been assigned a competent basis and a working method, while the latter appears to find such a basis in the pervasive rigidity of the outer half of the earth implied by various astronomical and physical data, provided depths of several hundred miles, affected by high rigidities throughout, are assumed to act in strict co-ordination in withstanding deformation during the period of stress accumulation. There are, therefore, serious grounds for hesitating to accept conclusions involving fluidal or viscous mobility beneath a shallow sub-crust, unless the evidence is direct and specific.

If that portion of the paper which relates to rigidity and isostasy be put into the category of inferential and interpretative matter, to which there are at least recognized, if not plausible, alternatives, the positive determinations, standing as they seem to do on a firm basis, may well be regarded as constituting a contribution of the first order of importance.

T. C. C.

To anticipate any misapprehension that might have crept into the foregoing review or that might grow out of it, the manuscript was submitted to the authors of the paper with an invitation to suggest points of revision or to add a statement to go with it. In response to this, the following comments have been prepared by Mr. Hayford. In the light of these, the review might well be modified at some points, but to avoid disturbing the basis of Mr. Hayford's comments it is left precisely as submitted.—T. C. C.

COMMENT ON THE ABOVE REVIEW BY MR. JOHN F. HAYFORD

The Report reviewed on the preceding pages by Professor Chamberlin, is essentially a preliminary statement. It was necessarily short, being one of many presented by various countries to the International Geodetic Association for publication in its triennial report. Another short preliminary statement in regard to the same investigation is also available in print, in the *Proceedings of the Washington Academy of Sciences.*[1] Both of these statements are subject to defects due to brevity. So, also, must the statement here made be brief and defective. It is hoped that a much more complete statement of the investigation may be published by the Coast and Geodetic Survey within a year from date.

The fair and clear review by Professor Chamberlin is welcomed by the undersigned. A few statements seem to be necessary, in justice to the geodetic investigation under discussion, in order that there may be no misunderstanding.

Professor Chamberlin's distinction between demonstration and interpretation, in connection with this investigation, is correct. The investigation demonstrates that the present distribution of densities follows a certain law. The statement of the meaning of this law in terms of rigidity is interpretation, and this interpretation depends, in part, on considerations outside the scope of the geodetic investigation. It seems to the writer, however, that the interpretation, given in terms of rigidity, is reasonably safe. When the interrelations of the geodetic and geologic evidence are more fully appreciated than at present, it is believed that others will reach the same conclusion.

Before discussing isostasy, it is necessary to get a clear conception of what the word means. It is stated in the review that certain language in the Report "carries the impression of a positive affirmation of liquidity or viscousness at the base of the crust in which the differentiated densities reside. Such is the usual conception that goes with the term 'isostasy,'

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[1] John F. Hayford, C.E., "The Geodetic Evidence of Isostasy, with a Consideration of the Depth and Completeness of the Isostatic Compensation and of the Bearing of the Evidence upon Some of the Greater Problems of Geology," *Proc. Wash. Acad. Sci.*, Vol. VIII, pp. 25–40 (May, 1906). The writer will be glad to furnish copies of this paper to interested persons.